Double-charm baryons: Possible multiquarks states containing heavy quarks

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Multicharm and multiquark states

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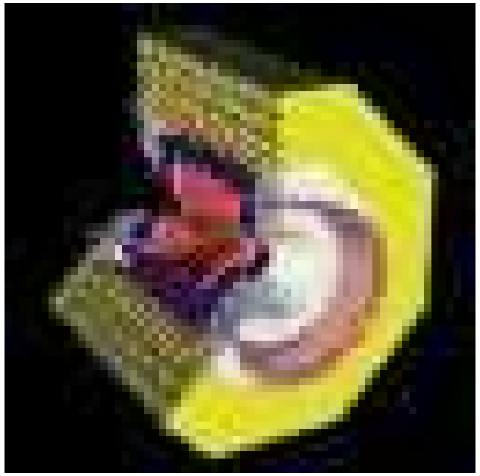
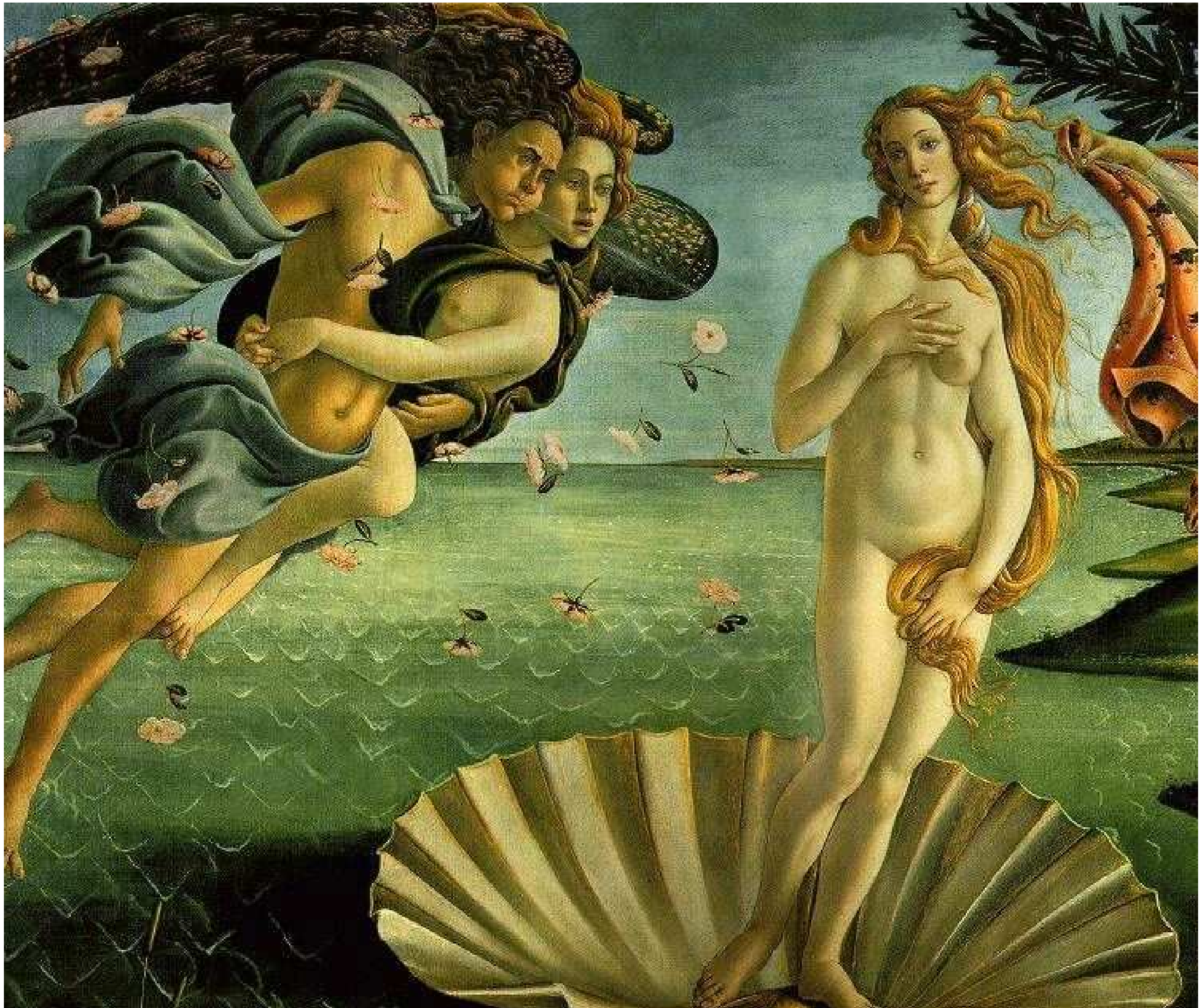


Outline

- Double-charm baryons
- Brief survey of multiquark candidates
- Tetraquarks with hidden or naked charm
- not covered here: weak decays of double charm

Single-charm baryons (as quark–diquark?)



Single-charm baryons-2

Qqq states tentatively described in a variety of models: potential, bags, etc.
Many data in recent years on ground and excited states with $S = 0$, $S = -1$ and $S = -2$. Minor problems, e.g., isospin splittings.
Note: Hierarchy of lifetimes OK
but the spread of values is larger than expected.

Spectroscopy of QQq baryons

Probably the most interesting among ordinary hadrons to study confinement dynamics.
It combines:

the slow $Q - Q$ relative motion, as in quarkonia

the relativistic q motion, as in D's and B's.

Two main strategies:

- diquark–quark
- Born– Oppenheimer

The first excitations are mainly in $Q - Q$.

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Diquark–quark picture

For sure $Q - Q$ clustering inside QQq.
Two steps strategy:

1. Calculate QQ
2. Calculate $[QQ] - q$

   Step #2 is O.K. But in step #1, care that $V(QQ)$ is effective.

   In the H.O. model, $V = K(r_{12}^2 + r_{23}^2 + r_{31}^2)$ is exactly $V = 3/2 K r_{QQ}^2 + 2K r_{q-[QQ]}^2$. So 1/3 of QQ interaction comes from the q field.

   Similarly, in H_2^+, the $p - p$ force comes from the electron.

Born–Oppenheimer

Theorem: *The Born–Oppenheimer approximation works always better than expected.*

See, e.g., Fleck and R. (PTP, 1989). Two steps:

1. Freeze out r_{QQ}. Calculate the "electronic energy", i.e. the energy of q in the 2-centre problem.
2. $V_{\text{eff}}(QQ) =$ this energy + direct $Q - Q$.
   Then solve the $Q - Q$ problem

Results

Variants of the bag model also tried. Not very stable v.s. parameter changes.

Results of potential models rather stable vs. choice of potential

Typically:

- ccq ground-state near 3.6 GeV
- hyperfine splitting about 80 MeV
- orbital excitation about 300 MeV
- flavour excitation $(ccs) - (ccd)$ near 90 MeV.

Inequalities

Under reasonable assumptions, (See Lieb, Martin et al., Nussinov)
flavour independence implies

$$\mathcal{M}(M,M,m) \leq 2\mathcal{M}(M,m,m) - \mathcal{M}(m,m,m)\ ,$$

relating ccq to cqq and qqq, leading to a potential-independent

$$\mathcal{M}(ccq) \leq 3.7\, GeV$$

for the average of the hyperfine multiplet. Can be refined. Also $q \to s$.

Towards a better calculation

Stancu (Liege) + R. (project). Help welcome.
Use the Born–Oppenheimer approximation,
with a better treatment of light quark dynamics for fixed r_{QQ}, e.g.,

- lattice QCD [a]
- relativistic equation probed for D mesons

Progress expected.

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[a] A direct lattice study (without Born– Opennheimer) recently published by Flynn et al., UKQCD

Multiquarks: 1. Possibly related to our discussion

- many scalar mesons $\rightarrow qq\bar{q}\bar{q}$?
- including perhaps $I = 2$ exotics
- Light pentaquark $S = +1$ seen in several experiments
- $D^*_{s,J}$ possibly a kind of multiquark

17) **HINTS FOR A I = 2 PI PI RESONANT STATE IN THE ANTI-N P --> PI+ PI+ PI- ANNIHILATION REACTION.**
By OBELIX Collaboration (A. Filippi *for the collaboration*). 2001.
Prepared for Biennial Conference on Low-Energy Antiproton Physics (LEAP 2000), Venice, Italy, 26 Aug 2000.
Published in **Nucl.Phys.A692:287-294,2001**

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Multiquarks: 2. H

Jaffe: H $(uuddss)$ 150 MeV below $\Lambda\Lambda$ threshold

Due to chromomagnetic forces (or bag model analogue)

$$-g\sum_{i<j}\frac{\tilde{\lambda}_i.\tilde{\lambda}_j\,\sigma_i.\sigma_j}{m_i m_j}\,\delta^{(3)}(\mathrm{r}_{ij})$$

Hardly survives:
- SU(3)$_F$ breaking
- Other terms in the Hamiltonian
- A realistic $\langle\delta^{(3)}(\mathrm{r}_{ij})\rangle$

H search in many exp., e.g., ${}^{6}_{\Lambda\Lambda}\mathrm{He}\to H+\alpha$ not seen.

Multiquarks: 3. Heavy pentaquark P

P Proposed by Gignoux et al. and by Lipkin (1987)
$P = \overline{Q}qqqq$ with $qqqq = uuds, udds$ or $udss$.
150 MeV below $D + \Lambda$ threshold?

Also due to chromomagnetic forces

Binding suffers from:
- $M(Q) < \infty$
- $\mathrm{SU}(3)_F$ breaking
- Other terms in Hamiltonian
- A realistic $\langle \delta^{(3)}(\mathrm{r}_{ij}) \rangle$

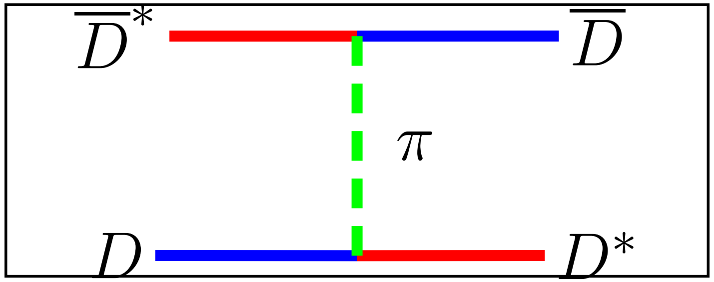
P search at Fermilab (Ashery et al.). Next: Compass

4. Hidden-charm tetraquarks $Q\overline{Q}q\bar{q}$

Cf. Belle state at 3.8 GeV

Already proposed for $\Psi(4.03)$, which turned out to be $c\bar{c}$

A long history, see Okun, Voloshin, De Rujula et al., Törnqvist , Manohar and Wise, Ericson and Karl, etc.



Yukawa potential $V = -g\exp(-\mu r)/r$, g weaker than for NN, but mg OK. $D\overline{D}^*$ nearly bound. $B\overline{B}^*$ probably.

Short range interaction? (repulsive?)

5. Double-charm tetraquarks $QQ\bar{q}\bar{q}$

$QQ\bar{q}\bar{q}$ studied in quark model or lattice by Ader et al. (then at CERN), Heller et al. (Los Alamos), Zouzou et al. (Grenoble), Lipkin (Argonne), Silvestre-Brac et al. (Grenoble), Brink and Stancu (ECT*, Trento), Rosina et al. (Slovenia), Michael et al. (UKQCD), etc., See, also, T. Barnes.(Oak Ridge), Nussinov

All agree! stable, i.e., below the threshold $(Q\bar{q}) + (Q\bar{q})$, if M/m large enough.

$QQ\bar{q}\bar{q}$ (Cont.)

This is a chromoelectric effect. In a flavour-independent potential, heavy particles enjoy more binding.

If flavour independence is taken seriously, even for light quarks, then close analogy with

atomic physics:
- $\mathrm{Ps}_2(e^+, e^+, e^-, e^-)$ weakly b.
- $\mathrm{H}_2(p, p, e^- e^-)$ more deeply b.
- $\mathrm{H}\overline{\mathrm{H}}(p, e^+, \bar{p}, e^-)$ unstable

In simple quark models:
- $(qq\bar{q}\bar{q})$ unbound
- $(QQ\bar{q}\bar{q})$ stable if $Q \gg q$
- $(Qq\overline{Q}\bar{q}$ unbound without LR

$QQ\bar{q}\bar{q}$ (Cont.)

In the limit of large M/m, remarkable structure

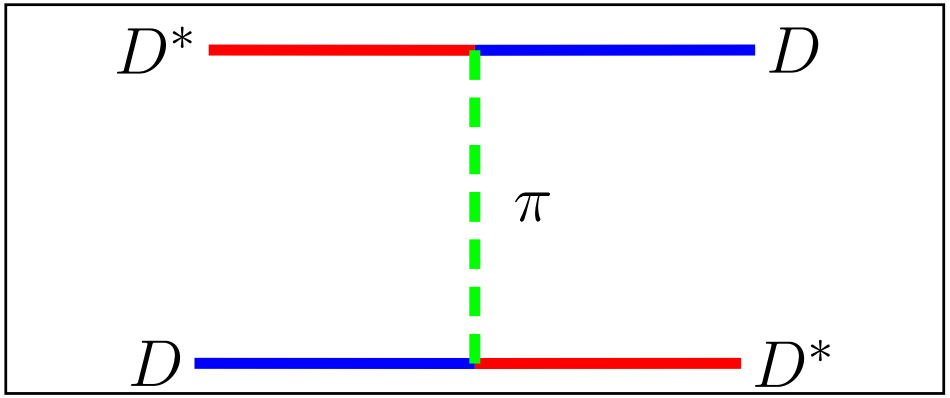
- $Q + Q \to (Q, Q)$ with colour $\bar{3}$ as in baryons.
- $(Q, Q)_{\bar{3}} + \bar{q} + \bar{q} \to$ colour singlet like in every antibaryon.

So well known colour structures and wave functions, unlike the more speculative colour chemistry of Chan H.M. et al.

Charmed quark c perhaps not heavy enough, BUT

$QQ\bar{q}\bar{q}$ (Cont.)

Other approach by Törnqvist (Helsinki), Manohar and Wise, Ericson and Karl



Yukawa potential $V = -g\exp(-\mu r)/r$ between D and D^*.
Coupling g weaker than for NN, but $m(D) > m(N)$.
What matters is mg.

π- exchange a little marginal to bind DD^*.

$QQ\bar{q}\bar{q}$ (end)

A proper combination of

- short-range attraction, as given by UKQCD or quark models
- long-range attraction, due to π-exchange

could well give $\boxed{\text{a stable tetraquark with charm = 2}}$

Conclusion: double charm

Interesting weak decay

ccq: laboratory for confinement, in particular

Aspects of light quark dynamics enhanced

Possibility of exotics with heavy flavour

Lessons from recent findings

Light quark dynamics might be more subtle than the simple chromomagnetic interaction of Jaffe, Lipkin, etc.

$QQ\bar{q}\bar{q}$ Arguments based on flavour independence, analogy with atomic physics probably OK. However, the role of meson–meson long-range interaction is crucial.

Beyond double charm

TRIPLE CHARM

ccc

Ultime goal of baryon spectroscopy (Bjorken)

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